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Byram's Energy Criterion for Wildland Fires: Units and Equations

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Abstract—The equations presented by G. M. Byram in 1959 for calculating energy flow rate in the wind field (P_w) and in the convection column (P_f) above a wildland fire are inconsistent because units for each rate are not those of an energy rate (or power) per unit area. New equations for P_w and P_f are introduced, and sample calculations are presented for the British gravitational and SI systems of units.

Keywords: convection columns, blowup fires, fire behavior

The concepts of energy flow rate in the wind field and in the convection column above a line of fire were introduced by G. M. Byram (1959). The energy flow rate in the wind field (P_w) is a rate of flow of kinetic energy through a vertical plane of unit area at a specified height in a neutrally stable atmosphere, one in which the temperature of unsaturated air decreases 9.8 °C per kilometer of height above the earth's surface. The energy flow rate in the convection column above a line of fire (P_f) is the rate at which thermal energy is converted to kinetic energy at the height specified for P_w in the convection column. Byram pointed out that his case studies of several wildfires had shown that the ratio P_f/P_w can be useful in understanding and predicting the onset of erratic fire behavior and the occurrence of blowup fires. According to Byram, his studies demonstrated a strong relationship between the occurrence of blowup fires and values of P_f/P_w equal to or greater than 1 for at least 1,000 feet above the fire.

Other fire researchers have used the P_f/P_w concept. It has been used in Australian and Russian studies of spotting and crown fire spread (Cheney and Bary 1969; Kurbatsky 1969; Mateev and Mateev 1977). In the United States, Wade and Ward (1973) and Simard and others (1983) used P_f/P_w in the analysis and interpretation of wildfire behavior. Aronovitch (1989) suggested using P_f/P_w to forecast the occurrence of blowup and to estimate the height of the convection column. He recommended that wind profiles needed for computing P_w be made a part of fire management systems such as BEHAVE. Rothermel (1991a) developed a chart for estimating the rate of spread, rate of energy release, and flame length of crown fires in the Northern Rocky Mountains. He then used P_f/P_w to predict whether a given fire will be wind-driven (with a plume tipped away from vertical in the direction of the wind) or plume-dominated (with a convection column standing

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nearly vertical). In addition, Byram and others (1964) compared P_f/P_w with observations of flame characteristics in a laboratory wind tunnel study. More recently, Martin and others (1991) used P_f/P_w to study how flame angle is related to windspeed for laboratory pool fires, fires in which liquid fuels are burned in pans or trays.

With the increasing interest in using P_f/P_w to interpret and characterize the behavior of wildfires and smaller scale fires, it is likely that fire managers and fire researchers will become aware of an inconsistency in the units of P_w and P_f in Byram's original work (1959) and in later documentation (Brown and Davis 1973). The problem is as follows: units of P_w and P_f are given as ft·lb/ft^2·s, where lb must refer to pounds force to obtain a flow of energy. Substitution of units into the equations, however, shows that lb in the numerator of P_w and P_f has units of pounds mass rather than pounds force. This inconsistency may be a source of confusion for persons not familiar with the systems of units commonly employed in the physical sciences. The problem also becomes evident when one wishes to calculate P_w and P_f separately in units differing from those given by Byram.

This note (1) demonstrates the inconsistency in units of the original P_w and P_f equations, (2) introduces a general version of the equations valid in any system of units, (3) describes conversion factors required for calculating P_w and P_f in the British gravitational and SI systems, and (4) presents sample calculations in the British and SI systems using the general equations.

ORIGINAL EQUATIONS FOR P_w AND P_f

The original equations for P_w and P_f in a neutrally stable atmosphere as given by Byram (1959) are

$$P_w = \rho(v - r)^3/2g \tag{1}$$

$$P_f = I/c_p(T_o + 459) \tag{2}$$

where P_w is the rate of energy flow in the wind field at height z above a fire and P_f is the rate at which thermal energy is converted into kinetic energy in the convection column at height z. The quantities in equations (1) and (2) and their units in the British system are

ρ = air density at height z, lbm/ft^3
v = windspeed at height z, ft/s
r = forward rate of spread, ft/s
g = acceleration of gravity, ft/s^2
I = fireline intensity, Btu/ft·s
c_p = specific heat of air at constant pressure, Btu/lbm·°F
T_o = free-air temperature at the elevation of the fire, °F.

In the strictest sense, units of energy in the British system are ft·lbf, but the energy units divide out cleanly in the ratio I/c_p of equation (2). Thus, the more familiar Btu of energy is used here. Substitution of units into equations (1) and (2) shows that both P_w and P_f have units of lbm/ft·s, or ft·lbm/ft^2·s when multiplied by the ratio ft/ft. Only for a system of units in which 1 lbf = 1 lbm will equations (1) and (2) provide numerically correct answers. In general, the equations are not formulated with the anticipation of possible use in other systems of units.

The inconsistency in units is related to Newton's second law of motion, $F = ma = mg$, and to the use of absolute or gravitational units in the equations for P_w and P_f. In Newton's law, F denotes a force, m is a mass, a is an acceleration, and g is the acceleration due to gravity. In an absolute system, such as the SI system of units, there is one unit for each physical quantity and the product mg equals the force F by definition of the units. In the gravitational system, however, mass is divided by a conversion factor that is numerically equal to g but has different units. This factor is denoted here by g_o, and Newton's law becomes $F = mg/g_o$. Thus, a force of 1 pound (1 lbf) is numerically equivalent to a mass of 1 pound (1 lbm). When g has its standard value of 32.2 ft/s^2, multiplication by the ratio g/g_o renders each equation consistent with respect to units because the conversion factor is given by $g_o = 32.2$ ft·lbm/lbf·s^2. Thus, g/g_o numerically equals 1, and equations (1) and (2) are better expressed as

$$P_w = \rho(v-r)^3/2g_o \tag{3}$$

$$P_f = gI/g_o c_p(T_o + 459). \tag{4}$$

Substitution of the appropriate units now leads to ft·lbf/ft^2·s, the units for P_w and P_f given by Byram (1959). For consistent units, equations (3) and (4) should be used in place of equations (1) and (2) when calculations of P_w and P_f are made in the British gravitational system.

GENERAL EQUATIONS FOR P_w AND P_f

Equations for P_w and P_f may be written in a form applicable to any system of units. Transformation from one system to another is easily accomplished if a table of conversion factors relating mass, force, and energy is available. The general equations correspond to equations (3) and (4), with g_o dimensionless and equal to 1. In addition, an absolute temperature is required in place of $(T_o + 459)$ in equation (4). The equations are

$$P_w = \rho(v-r)^3/2 \tag{5}$$

$$P_f = gI/c_p T_a \tag{6}$$

where T_a is the absolute temperature of air at the elevation of the fire in the units employed and all other quantities have been defined previously. Equations (5) and (6) correspond to the P_w and P_f relationships derived by Byram from consideration of the physical processes. I am writing an article presenting the derivation of P_w and P_f.

Factors are needed for converting from force to mass times acceleration and from force to energy per unit length. For the British and SI systems of units these factors are

$$\text{British: } 1 \text{ lbf} = 32.2 \text{ lbm·ft/s}^2 = 32.2 \text{ lbm·ft}^2\text{/ft·s}^2 \tag{7}$$

$$\text{SI: } 1 \text{ newton} = 1 \text{ kg·m/s}^2 = 1 \text{ J/m} = 0.001 \text{ kW·s/m}. \tag{8}$$

These identities, when used with equations (5) and (6), facilitate calculation of P_w and P_f in units of energy per unit time per unit area, or equivalently, power per unit area (Martin and others 1991; Rothermel 1991b).

SAMPLE CALCULATIONS

Suppose that at some specified height in the atmosphere above a line fire the quantities ρ and v have values in British units of 0.0695 lbm/ft^3 and 20 ft/s, respectively. Further suppose the forward rate of fire spread is 2 ft/s and the corresponding fireline intensity is 15,000 Btu/ft·s. At the elevation of the fire, c_p and T_a have values of 0.24 Btu/lbm·°R and 540 °R. These quantities are used with tables of conversion factors to compute P_w, P_f, and the ratio P_f/P_w in the British and SI systems; the calculations are given below. The SI calculations are checked by conversion back to the British system, illustrating the transformation from one system of units to another.

British: From equations (5) and (7),

P_w = [0.0695 lbm/ft^3 · (20 – 2)^3 ft^3/s^3][1 lbf·ft·s^2/32.2 lbm·ft^2]/2 = 6.30 ft·lbf/ft^2·s.

From equations (6) and (7),

P_f = [32.2 ft/s^2 · 15,000 Btu/ft·s][1 lbf·ft·s^2/32.2 lbm·ft^2]/[0.24 Btu/lbm·°R · 540 °R] = 115.74 ft·lbf/ft^2·s

and P_f/P_w = 115.74/6.30 = 18.37.

SI: Suppose the fire and atmospheric variables presented earlier are available in SI units. Then

ρ = 1.11 kg/m^3
c_p = 1,003.9 J/kg·K
T_a = 300 K
v = 6.1 m/s
r = 0.61 m/s
I = 5.19 · 10^4 kW/m
g = 9.8 m/s^2.

From equations (5) and (8),

P_w = [1.11 kg/m^3 · (6.1 – 0.61)^3 m^3/s^3][0.001 kW·s/m/1 kg·m/s^2]/2 = 0.0918 kW/m^2.

From equations (6) and (8),

P_f = [9.8 m/s^2 · 5.19 · 10^4 kW/m][1 J/m/1 kg·m/s^2]/[1,003.9 J/kg·K · 300 K] = 1.69 kW/m^2

and P_f/P_w = 1.69/0.0918 = 18.41, in close agreement with the computation using the British system.

Values of P_w and P_f in SI units are converted to British units as follows:

P_w = 0.0918 kW/m^2 · 1 ft·lbf/0.001356 kW·s · 1 m^2/10.76 ft^2 = 6.29 ft·lbf/ft^2·s

where use is made of the identities 1 ft·lbf = 1.356 J = 0.001356 kW·s and 1 m^2 = 10.76 ft^2.

Similarly,

P_f = 1.69 kW/m^2 · 1 ft·lbf/0.001356 kW·s · 1 m^2/10.76 ft^2 = 115.83 ft·lbf/ft^2·s.

The negligible difference in P_w and P_f values between the two systems is due to rounding errors.

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